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Direct Drive Wave Energy Array with Battery Storage for Off Grid Operation

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Keywords: energy storage, wave energy converter, wave array, point absorber, direct power control.

Abstract

Direct drive permanent magnet linear generator have been proposed as an alternative to conventional generators due to the simplification they introduce in a wave energy converter system. Due to the ability of the permanent magnet generators to generate power at low speeds it is possible to generate power from low power waves using small wave energy devices. The low power wave energy converters can form arrays to supply power to remote coastal or island communities which are off-grid. The paper introduces wave-to-wire modelling of wave energy arrays for off-grid systems using low power permanent magnet linear generators. A new battery storage at the DC link is introduced to keep the voltage constant along with a direct power controller for the inverter in order to supply quality power to the domestic load connected off-grid. Results are presented that show the system under different operating conditions such as sub-optimal and reactive control as well as extreme conditions of high load demand.

1 Introduction

Island communities and rural coastal areas are often isolated from the electric network. For such areas the energy supply comes from autonomous diesel or oil fired generators. The utilisation of wave energy converters (WECs) for island communities and remote coastal areas can increase the reliability of supply, decrease the fuel cost needed for the fossil fuel generator and finally when the area is connected to the main electrical network the WECs can contribute to the overall renewable energy production. However, due to the variability of the resource, the energy WECs produce cannot be directly used at domestic level [1]. Power smoothing and quality improvement is needed. In this research paper a different approach is proposed, from what appears in the literature [2,3], in order to increase the power quality output of the WEC array using battery storage (BS) at the common DC link and direct power controller (DPC) for the inverter to supply constant power at the residential load.

The wave energy resource [4] is significant and can contribute to the demand for renewable electricity. However,

large amount of the wave energy resource can be characterised as “low” and can be found in many areas around the world such as the Chinese coastline and the Mediterranean Sea [5]. One of the key focus of this paper is to investigate the application of a low power WEC array to supply power to an off-grid residential load.

At the moment a number of different designs exist that convert wave energy to electrical power. These designs usually have power take-off systems that use conventional high speed rotating electrical generators such as induction and synchronous machines [6]. For WECs that are based on the point absorber concept it is suggested that a direct drive (DD) power take-off system that uses permanent magnet linear generators (PMLG) can be a viable alternative with Archimedes Wave Swing (AWS) to be one of the most known examples [7, 8]. By using DDPMLGs for WECs the complex mechanical interface between the prime mover and the rotor is eliminated and the conversion losses are reduced. In addition, in a Vernier hybrid machine (VHM) operation speeds are low as dictated by the incoming waves and the construction of the machine is not as complicated as other traverse flux permanent magnet machines. However, cost and complexity of PMLG is higher than conventional machines and in addition special design needs to be introduced in order to avoid high eddy-current losses [9, 10].

The aim of this research paper is to provide a wave-to-wire system model of a complete wave energy conversion array for off grid operation. For this reason in section 2 all the different parts of the model are described including the generator, the controller, the common DC link for the array, energy transmission to shore and the grid side controller. In section 3 the overall operation of the system is described under reactive and sub-optimal control of the PMLG using regular, monochromatic waves. In section 4 results are presented regarding the power quality at the domestic side of the system under different extreme conditions. Finally conclusion are presented in section 5.

2 System description

This section describes the wave-to-wire system model developed in MATLAB/Simulink. The block diagram of the proposed electrical configuration of the WEC array for off-grid operation is shown in Figure 1.

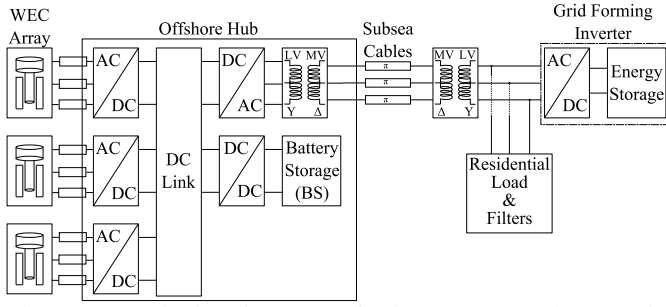


Figure 1: Block diagram of the wave-to-wire model developed in MATLAB/Simulink

The WEC array developed is composed of three WECs. Each WEC has short three phase cables to the offshore hub and it is directly connected to an active rectifier. Active rectifiers are controlled independently and convert AC current to DC. The DC outputs from all the active rectifiers are then connected to a common DC link. In order to keep the DC link voltage constant BS is included in the offshore hub. A DC/DC converter is utilised to step-up the voltage of the battery to the DC link voltage level. The DC/AC inverter is controlled so that a specific amount of power is transferred to shore based on the average power produced by the WEC array. In order to transfer power from the offshore hub to the shore medium voltage AC transmission is implemented using transformers. On the shore the grid forming inverter acts as a grid keeping the voltage constant and providing active and reactive power to the residential load if needed. For the purposes of this research the energy storage of the grid forming inverter is supposed to be able to provide autonomy to the system for a long period of time.

2.1 The generator and generator controller

The point absorber model in this paper is represented using a mass spring damper system as shown in Figure 2. The point absorber parameters are given in Table 1 and the equation of motion in (1). It is assumed that the point absorber is moving only at the heave direction with one degree of freedom and that the damping is linear. The point absorber model used in this research is a simplified model as the main focus is on the electrical side of the WEC arrays.

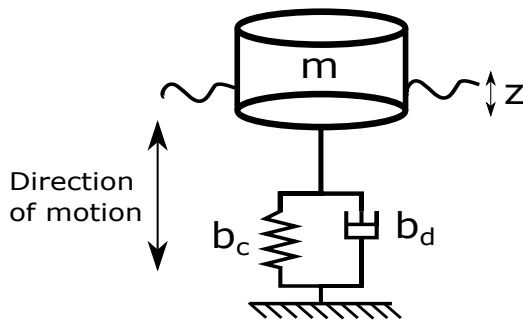


Figure 2: Block diagram of the mass spring damper representing the point absorber.

$$m \cdot a + b_d \cdot v + b_c \cdot z = F_{wave} \quad (1)$$

Where m is the mass, b_d is the damping coefficient, b_c is the spring stiffness, a the acceleration, v the velocity and z the displacement of the point absorber. More details regarding the design, modelling and control of the DDPMLG can be found in [11] – [13]. It is noteworthy to mention that for the reactive control of the DDPMLG power must be absorbed by the generator at the end of the half period of the wave in order to maximise power output [14]. The BS connected at the DC link ensures that this power comes from the DC link and not from the onshore grid forming inverter which would incur more losses.

Parameters	Value
WEC peak rating	30 kW
WEC average power	9 kW
Mass (m)	10000 kg
Damping (b_c)	4000 Ns/m
Stiffness (b_d)	31580 N/m
Absorber natural frequency	1.7771 rad/s
Buoy radius	1.5 m

Table 1: Point absorber and generator parameters.

2.2 DC link and battery storage

At the DC link all the power from the WEC array is collected. The DC link is modelled as a capacitor with internal resistance. In Table 1 the DC link parameters are given. In addition, at the DC link the BS is connected using a DC/DC converter to step-up the voltage from the battery voltage of 48V to the DC link voltage of 800V. The purpose of the BS is twofold:

Firstly, the battery is responsible for keeping the DC link voltage constant at 800V. This is achieved by using a DC/DC cuk converter that steps up the voltage of the batteries from 48V to 800V and allows bi-directional power flow between the battery and the DC link. With variable power input at the DC link, from the WEC array, the BS has to be able to accept this amount of power which is above the power the DPC controller delivers to the load. In the time period of a regular wave the generator reaches the peak power twice. In that period of time the BS has to be able to absorb all the energy which is higher from the active power delivered to the load and release the energy absorbed when power delivered is higher from the power produced by the WEC array. Figure 3a describes this process for a single device and Figure 3b for a WEC array of three devices that operate at different phases. In a WEC array that is composed from several devices operating at different phases the power input is smoother. Based on [15,16] the battery storage required is calculated to be able to store ten periods of rated energy from the WEC array. Based on Table 1 this leads to an 8Ah, 12V battery per WEC device which is significantly small.

Secondly, the battery will supply the WEC array any amount of active or reactive power required by the reactive power controller. As previously stated in order to perform reactive power control, and extract the maximum amount of power

from the waves, the controlled WEC has to absorb power from the system at some instances. For this reason the battery capacity has to be readjusted from the calculations described above. To sum up, the BS for a low power WEC array can be composed from small and cheap batteries widely used in domestic applications. DC link and BS parameters are given in Table 2.

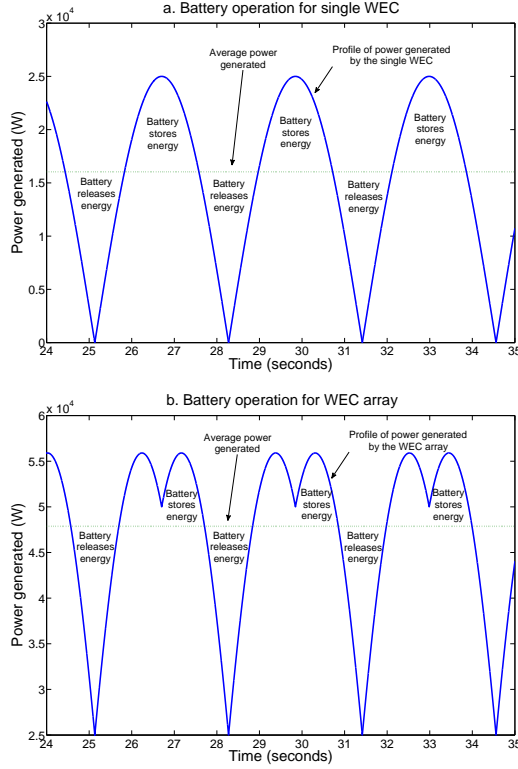


Figure 3: Calculation of the rating for the battery storage at the DC link. a. for a single WEC b. for WEC array of three devices using sub-optimal control.

Parameters	Value
DC link voltage	800 V
DC link capacitance	20 μ F
Battery voltage	48 V
Battery rating	1500 Wh

Table 2: DC link parameters.

2.3 Direct power controller

The power generated by the WEC array is variable and power quality improvement is needed before it is used for domestic purposes. In most research papers in the literature [2] power quality improvement is achieved on the onshore substation with the use of a DC/DC converter and a DC/AC converter. Instead, in this paper the DPC is proposed to control the power flow to the load [17]. Using a DPC the active and reactive power supplied by the inverter are defined by reference values. In the case of the proposed WEC array reactive power reference value is set to zero and active power reference value is set by an algorithm that takes into account the power generated by the array, the losses in the system and

the state of charge of the DC link battery. The block diagram of the DPC is shown in Figure 4 and the equations in (2) – (3).

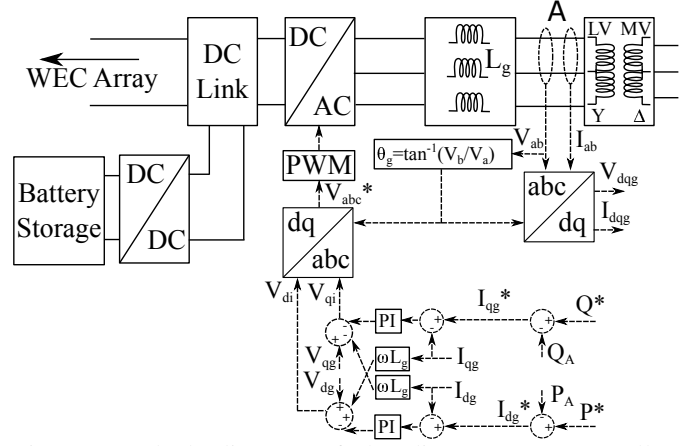


Figure 4: Block diagram of the direct power controller. Measurements are taken from point A.

$$v_{di} = -PI(s) \cdot (i_{dg}^* - i_{dg}) + \omega_g \cdot L_g \cdot i_{qg} + v_{dg} \quad (2)$$

$$v_{qi} = -PI(s) \cdot (i_{qg}^* - i_{qg}) - \omega_g \cdot L_g \cdot i_{dg} + v_{qg} \quad (3)$$

The active power reference value (P^*) is derived by the algorithm shown in (4):

$$P^* = P_{dc}^{2s} \cdot \eta \cdot B_{SOC} \quad (4)$$

Where P_{dc}^{2s} is the average DC link power delivered by the WEC array calculated every 2 seconds, B_{SOC} is the state of charge of the battery and η is the DC link efficiency. This algorithm ensures that the higher the state of charge the higher the amount of power will be delivered to the load. If the battery is discharged significantly then the algorithm will make sure that the state of charge of the battery will not drop by reducing the amount of power delivered to the grid. Using this algorithm it is observed that the DPC works independently from the state of charge of the grid forming storage element and the domestic load. By doing that the maximum active power is delivered from the WEC array to the load. Finally the voltage pulses generated by the DPC are synchronised to the grid forming inverter by using a phase lock loop (PLL).

2.4 Energy transmission

Energy is transmitted to shore by using medium voltage AC cables. The voltage output from the inverter at the offshore hub is 400V. The transformer steps-up the voltage to 13.2kV in order to have reduced losses in the cables. The three phase subsea cables are modelled using the π -section. Distances from low power WEC arrays will be short and therefore 1km of distance is considered. The onshore transformer steps-down the voltage from 13.2kV to 400V for residential use. The parameters of the transformers and cables are given in Table 3.

Parameters	Value
Cable length	1 km
Cable resistance	0.197 Ω /km
Cable inductance	0.742 mH/km
Cable capacitance	0.311 μ F/km
Transformer rating	200 kVA
Wye resistance	0.02 pu
Wye inductance	0.02 pu
Delta resistance	0.01 pu
Delta inductance	0.01 pu

Table 3: Transformer and cable parameters.

3 System operation results

3.1 Simulation under different generator control options

Simulation results presented in this section are based on a regular wave of 1 rad/s (period of 6.28 seconds). Two cases are shown:

- System operation during sub-optimal control. The generator does not require any power from the DC link.
- System operation during reactive control where the generator at the end of the half period requires small amount of power in order to extract maximum power from the waves.

In both cases at 121 seconds a resistive load of 15kW is added to the system and at 132 seconds an additional 6kvar inductive load is added to the system.

Results from the operation of the WEC array with sub-optimal control are presented in Figure 5a and with reactive control in Figure 5b.

It is observed that in both cases presented in Figure 5 the DC link voltage is kept constant at 800V with small variations. The variations are more significant in the case of reactive control where power peaks are higher and instantaneous power drops below zero as it can be seen from Figure 5b. Similar trend appears at the state of charge of the DC link battery. Regarding the power generated in the two cases, as it is expected reactive controller generates higher average power compared to the sub-optimum controller but with higher power peaks as well. Similarly power exported from the DPC controller (P_{exp}) and power at the terminals of the grid forming inverter are higher in the case of reactive controller.

At 121 seconds a domestic load of 15000W is connected at the grid forming inverter's terminals as shown in Figure 1 at three different timings. Power exported by the DPC controller remains unaffected by the change of load since P^* is independent variable as stated in equation (4). Power delivered to the grid forming inverter (P_{load}) drops since P_{exp} is now used to supply the load. At 132 seconds and additional inductive load is connected. The inductive load does not affect the operation of the system and all the inductive demand is supplied by the grid forming inverter. However,

the inductive load increases power ripples of the power delivered to the grid forming inverter. In the following section the operation of the system under high load demands is depicted.

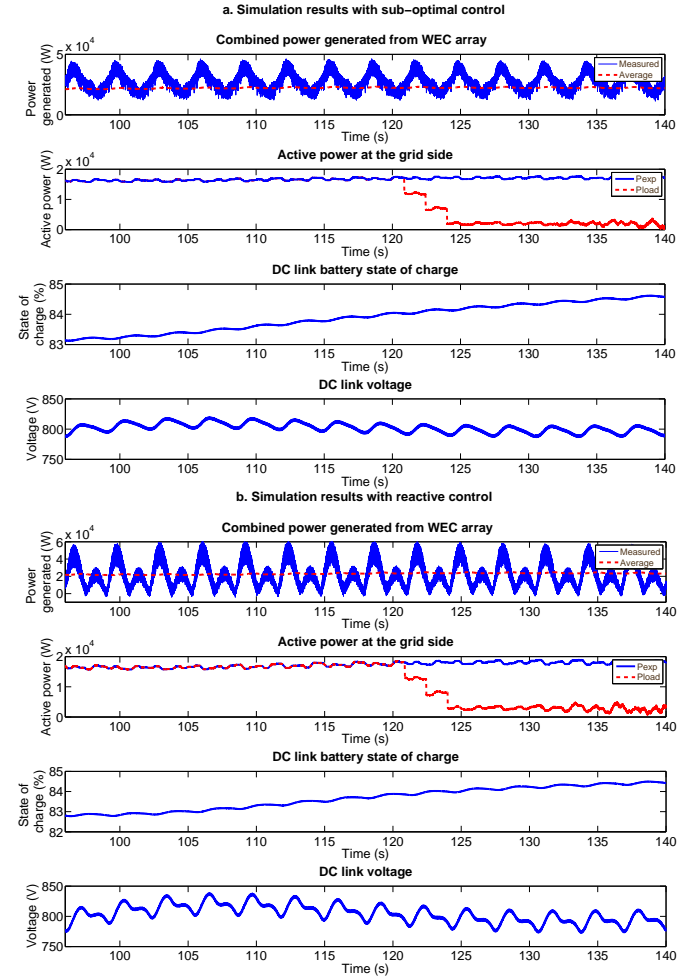


Figure 5: Results from the operation of the WEC array for a. Sub-optimal control b. reactive control.

3.2 Simulation under high load

Simulation results in this section deal with the effect of high load demand at the system presented. Two cases are presented based on the WEC array with input a regular wave of 1 rad/s. In both cases the high power demand cannot be supplied by the WEC array and therefore the grid forming inverter supplies the rest of power (negative active power)

- High active power demand by increasing the resistive load to 30kW.
- High positive reactive power demand by increasing the inductive load to 15kvar.

In both cases the loads are connected at 77 seconds.

The results from the operation of the system under these conditions are presented in Figure 6a for the resistive load and Figure 6b for the inductive load.

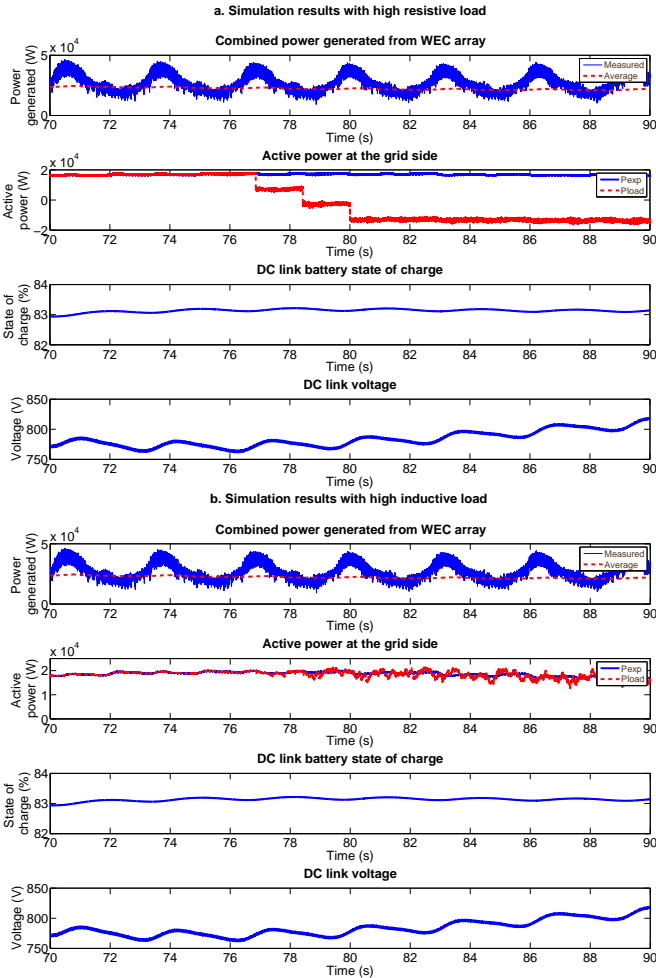


Figure 6: Results from the operation of the WEC array under high loads. a. High resistive load b. high inductive load

In both cases presented in Figure 6 the power generated, the state of charge of the battery and the DC link voltage are unaffected by the changes at the grid side. In addition power delivered by the DPC (P_{exp}) controller is based on equation (4) and is independent from the load side. In Figure 6a the resistive load is higher than the power exported from the WEC array. In this case active power at the load turns negative which means that the rest of active power to the load is supplied by the grid forming inverter. In Figure 6b the inductive load is not supplied by the WEC array since reactive power reference is set to zero as described in section 2.3. Therefore, all the reactive power is delivered by the grid forming inverter discharging the storage element but at the same time active power from the WEC array is delivered to the grid forming inverter to charge the storage element.

5 Conclusion

In this paper a novel wave-to-wire model of a WEC array for off-grid applications is presented. The key contributions of this research is the addition of battery storage at the DC link to keep the voltage constant and the use of the direct power controller for the common inverter in order to deliver better quality active power to the residential load. The paper focuses

on the modelling of the battery system with the cuk converter and the modelling of the direct power controller. Results presented validate the use of this electrical configuration for off-grid applications. The WEC array, the DC link and the DPC controller are independent from the variations of the grid side while the DPC controller delivers active power to the domestic load. Future research will focus on the detailed modelling of the point absorber and of the domestic load.

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